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Towards Contrast Enhanced Breast Imaging using Ultra-Wideband Microwave Radar System

M. Klemm, J. Leendertz, D. Gibbins, I.J. Craddock, A. Preece, R. Benjamin

Department of Electrical and Electronic Engineering, University of Bristol, Bristol, United Kingdom

e-mail: m.klemm@bristol.ac.uk

ABSTRACT — In this paper we present numerical results of contrast-enhanced breast imaging using ultra-wideband microwave radar system. Due to low contrast in electrical properties between dense breast tissues and malignant tissues, tumor detection using microwave might be extremely challenging. To overcome this problem, we propose here a radar imaging technique based on a localized contrast enhancement. Our results show that microwave contrast agents able of changing an effective dielectric constant of cancerous tissues by only 1% would greatly improve imaging performance.

Index Terms — ultra-wideband (UWB) radar, microwave imaging, antenna array, contrast agents, medical imaging.

I. INTRODUCTION

The most recently published data on electromagnetic (EM) properties of breast tissues [1] suggest that the contrast between healthy and malignant tissues might be significantly lower and also that the breast interior is more inhomogeneous than indicated by previously published data (e.g. [2]). Moreover, fibroglandular tissues have similar electromagnetic (EM) properties to tumors, which will make them difficult to distinguish. This most recent report disclosing a more challenging case for microwave breast imaging than previously thought, resulted in the development of realistic numerical breast phantoms based on magnetic resonance imaging (MRI) [3], [4].

In a case of fibroglandular tissues, which dominate in dense breasts, results from [1] suggest that there might be only 10% dielectric contrast between healthy and malignant tissues. This would obviously seriously question possibility of breast cancer detection using microwaves [5] (either radar or tomographic system). Similar problems of imaging of dense breasts are well known for other modalities. In X-ray imaging a poor performance in dense breasts, usually those of younger women, results in screening being usually offered to older women. Also MRI images for dense breast tissues are not able in most cases to distinguish between normal and cancerous tissues. Improved visibility of tumors in very dense breasts has been achieved in MRI only with the help of contrast agents. The most commonly used compounds for MRI contrast enhancement are gadolinium (Gd) based. This intravenous contrast agent leaks out into tumors,

providing a localized change in the relaxation time of tissues picked up by the MRI system.

In this paper we propose contrast-enhanced microwave breast cancer detection in very dense breasts. Our rationale behind the proposed detection method is that by using a contrast agent we will be able to change locally effective electrical properties of malignant tissue. We hypothesize that these local changes would alter an electromagnetic (EM) response and could be detected using our developed microwave radar system. As a potential candidate for the contrast agent one could use nanoparticles. Metallic nanoparticles like gold nanoshells/nanorods, or iron oxides are capable of changing the EM signal. Magnetic nanoparticles (e.g. iron oxide) are of particular interest, as they should affect the effective magnetic tissue properties. This seems very attractive since all normal human tissues are non-magnetic. Magnetic nanoparticles were already applied in biomedical field as anticancer drug delivery vehicles [6], contrast agents for thermoacoustic imaging [7] and hyperthermia [8].

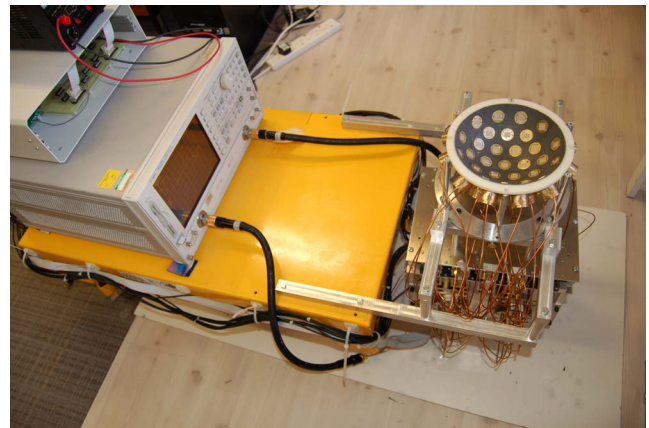


Fig.1. Microwave-radar system for breast cancer imaging developed at the University of Bristol.

II. UWB MICROWAVE RADAR IMAGING SYSTEM

In this contribution we present *numerical* simulations of contrast-enhanced microwave radar breast imaging. However, our numerical model of the radar system is based on a recently built *experimental* radar system [9] for breast cancer imaging presented in Fig.1. The main part of

the developed radar imaging system is the antenna array shown in Fig.2. This array is composed of 31 UWB wide-slot antennas [10], which are capable of transmitting very short EM pulses with wide frequency content. Detailed description of our system can be found in [5], [9]. Only for completeness we add that our radar operates in the multi-static mode. This means that each antenna transmits in turn a short UWB pulse, while the remaining antennas act as receivers. In this manner we collect 465 independent radar signals during a single scan. These signals provide an input to the beamforming algorithm, which forms a 3D image of the scattered energy.

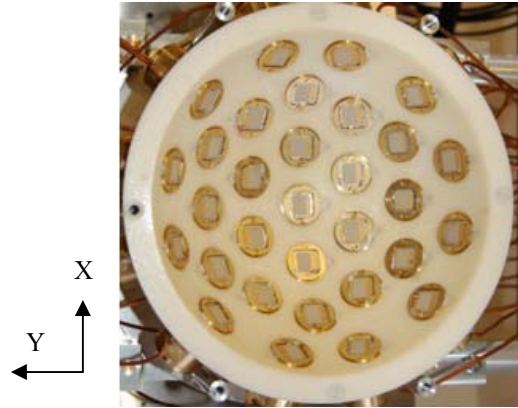


Fig. 2. Photo of the antenna array for breast cancer imaging (top view). Array is composed of 31 UWB wide-slot antennas operating between 3 and 10 GHz.

Below in Fig.3 we present the schematic view of the numerical antenna array composed of 31 UWB dipole antennas (seen in green). We employed dipole antennas in this study, instead of wide-slot antennas, because of their easy implementation in numerical solver (CST Microwave Studio) and low computational cost. To approximate the real array as closely as possible, we placed all dipole antennas in the same positions as real wide-slot antennas.

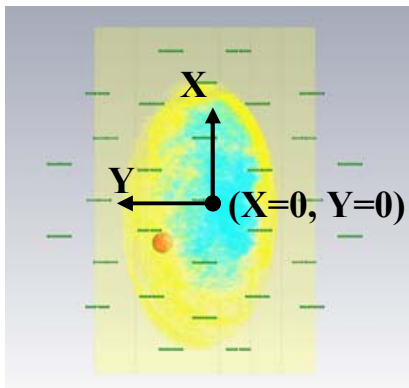


Fig. 3. Top view of the numerical antenna array, composed of 31 UWB dipole antennas, used in this study.

Moreover, we have oriented dipole antennas along the y-axis, to approximate the linear polarization of UWB wide-slot antennas in the real array.

III. NUMERICAL BREAST PHANTOMS

In the study we acquired data from 3-D numerical breast models, publicly on-line available at [11], having realistic distributions of dielectric properties. These models are based on MRI images of healthy breasts that have been categorized according to the Breast Imaging Reporting and Database System (BI-RADS) of the American College of Radiology (ACR).

In this study we use one particular breast model from [11], breast ID: 012304, which is classified as very dense (ACR class 4). The 3D view of this numerical breast phantom together with UWB dipole antennas is presented in Fig.4 below.

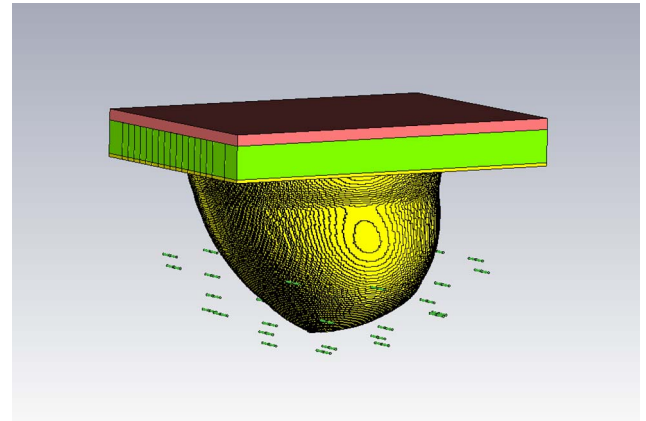


Fig. 4. Numerical setup for microwave-radar breast imaging. MRI-derived breast phantom is surrounded by the array of 31 dipole antennas.

Due to the limitations of the software, we assumed that breast tissues are divided into nine different types. Each tissue type is characterized by the Debye model and its parameters can be found in [11] (Instruction Manual, page 9, Table 3).

In Fig.5 we present examples of 2D cross sections through the breast phantom used in this work. Fig.5a shows the cross-section through the XY plane, and Fig.5b through the ZY plane. Both images are the maps of dielectric constant at 6GHz (scale shown in the color bar on the right hand side). As can be seen, tissue properties vary from around 10 to as high as 50 and have unstructured shapes. Moreover, tissues with very high dielectric constant clearly dominate in this breast phantom. In black we indicate position of the tumor, which is right within the very dense tissues.

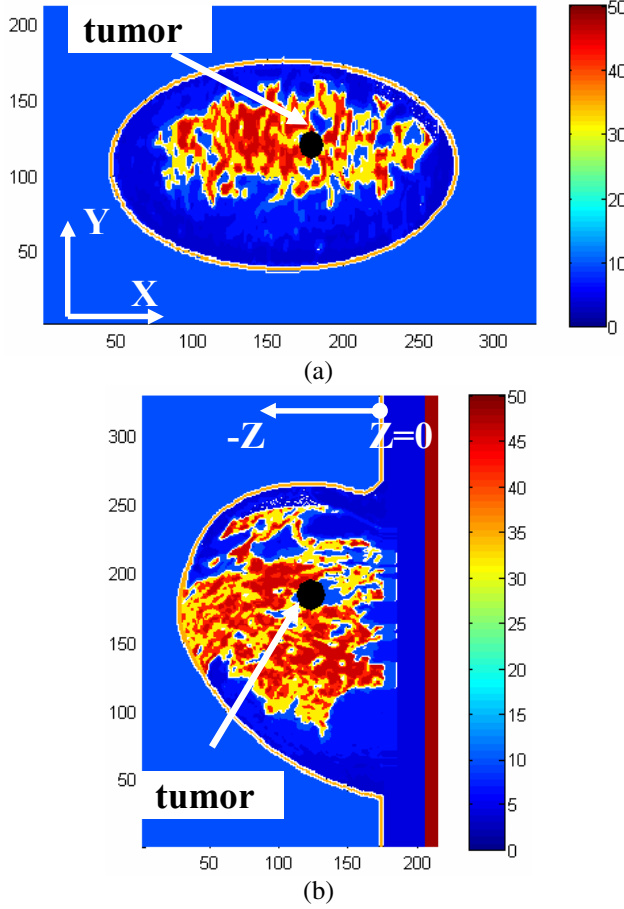


Fig. 5. 2D maps of dielectric constant for the very dense breast phantom used in this work: a) XY cross section, b) ZY cross section. Both images are taken through planes containing the tumor. Tumor positions indicated in black.

IV. CONTRAST-ENHANCED IMAGING SETUP

Using the numerical setup presented in Fig.4, we have performed two sets of simulations in order to obtain the contrast-enhanced radar imaging of breast cancer. In each set of simulations, all antennas were excited in turn by the UWB pulse while remaining antennas acted as receiving sensors. This process resulted in 30 3D simulations (with the reciprocity principle used) in each set and 465 independent radar signals. All simulation parameters were kept the same for both simulation sets, only tumor properties were changed. In the first set, we assumed the tumor to have the dielectric constant $\epsilon_r=50$ and conductivity $\sigma=7$ S/m. In the second set, we increased tumor's dielectric constant to $\epsilon_r=50.5$ and kept $\sigma=7$ S/m. This scenario assumes only 1% increase of the tumor's dielectric constant, due to the uptake of the contrast agent. This assumed change in electrical properties of the tumor

is somewhat arbitrary, but could be achieved in practice. Our rationale behind this hypothesis is based on the well known Maxwell-Garnett analytical model for dielectric mixtures [12]. According to the Maxwell-Garnett mixing rule for spherical inclusions, the effective permittivity of the mixtures is:

$$\epsilon_{eff} = \epsilon_b + 3 \cdot V \cdot \epsilon_b \frac{\epsilon_i - \epsilon_b}{\epsilon_i + 2\epsilon_b - V \cdot (\epsilon_i - \epsilon_b)}$$

where ϵ_b is the relative permittivity of the base material (tumor is this case; $\epsilon_b = \epsilon_r = 50$), ϵ_i is the relative permittivity of the inclusions, V is the volume ratio of inclusions and base material. If we use gold nanoparticles as the contrast agent, which has a conductivity of $4 \cdot 10^7$ S/m, its relative permittivity at 6GHz is $\epsilon_i = -j1.2 \cdot 10^8$. Assuming that the uptake of the contrast agent would result in gold inclusions filling only 0.33% volume of the tumor, would provide the effective permittivity $\epsilon_{eff} = 50.5$. This value of the tumor dielectric constant was used in the second set of simulations.

V. CONTRAST-ENHANCED IMAGING RESULTS

In Fig.6 and Fig.7 we present results of the hypothetical contrast-enhanced microwave radar imaging of breast cancer in very dense tissues. As a tumor model we used a 10mm-diameter sphere located at the position $x=10$, $y=20$, $z=-20$. Tumor relative to the breast tissues can be seen in Fig.5. Three dimensional (3D) imaging result is shown in Fig.6 as a contour map (values above -1.5dB relative to the maximum shown). As we can see, the resulting image gives a very clear detection of the single target.

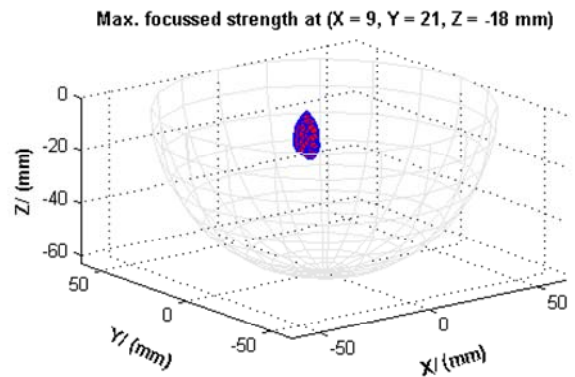


Fig. 6. 3D result of contrast-enhanced radar imaging of cancer in very dense breast. Figure presents -1.5dB contour map.

Below in Fig.7 we a two dimensional (2D) focused image is presented. Again, there is the very clearly only a single target detected, with very minor clutter signals present. Above results are very encouraging and show the great sensitivity of our radar imaging system. Moreover, these results suggest a high degree of clutter resistance of the multi-static radar system.

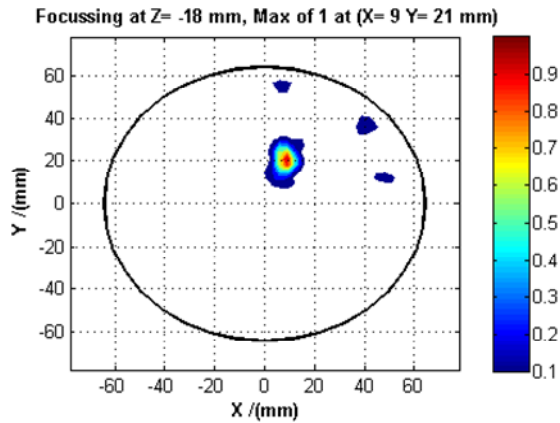


Fig. 7. 2D result of contrast-enhanced radar imaging of cancer in very dense breast. Contour plot shows signal energy on a linear scale, normalised to maximum in the 3D volume, values below 0.1 rendered as white.

VI. CONCLUSIONS

Investigations of the contrast enhanced UWB microwave radar imaging for breast cancer detection were presented in this work. Studies were performed by means of full-wave EM simulations. The numerical model of the UWB microwave radar was based on the experimental system recently developed at the University of Bristol. We showed that a minor change of 1% in the effective permittivity of the tumor is achievable by using gold nanoparticles as the contrast agent (assuming 0.33% volume ratio). This permittivity change is well detected with the UWB microwave radar system, as shown in our results. Future studies will include investigations of different breast phantom types, in terms of their tissue composition. Also, magnetic nanoparticles will be considered as a potential contrast agent.

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